|QBN〉

DIAMOND
QUANTUM TECHNOLOGIES

Enabling Robust and Scalable Quantum Systems for Real World Applications

Whitepaper

Executive Summary

Quantum technologies are becoming increasingly relevant for industrial competitiveness, security, and societal impact. As these technologies transition from research into early deployment, the choice of material platforms that support scalability, reliability, and integration with existing systems becomes decisive. Diamond-based quantum systems offer distinctive advantages in this context.

This white paper examines the potential of **Diamond Quantum Technology** (DQT), which exploits atom-scale defects in synthetic diamond, known as color centers, most prominently nitrogen-vacancy (NV) centers, to enable quantum computing, quantum communication, and quantum sensing. The document provides a structured and comparative overview of the technological foundations, application domains, ecosystem status, and market perspectives of diamond-based quantum technologies, with the aim of raising awareness of this hardware platform and positioning it in relation to alternative quantum and classical technologies.

Diamond Quantum Technology represents a distinct hardware platform within the broader quantum landscape. Its defining characteristics include long coherence times, optical addressability, solid-state robustness, and the potential for operation at or near room temperature. These properties enable quantum devices that are compact, energy-efficient, and resilient, opening pathways toward applications that extend beyond controlled laboratory environments.

Beyond technical performance, Diamond Quantum Technology is supported by a growing ecosystem of research institutions, startups, and industrial actors across the value chain, ranging from synthetic diamond growth and processing to device integration and application development. Establishing a shared understanding across these stakeholders is essential to accelerate progress and avoid fragmentation. This white paper therefore aims to contribute to a common language that bridges scientific, industrial, and policy perspectives.

Quantum Computing. Diamond Quantum Technology is poised to contribute significantly to quantum computing by enabling long coherence times and inherent stability through the use of NV centers in diamond, which serve as robust quantum bits (qubits) and support the development of scalable quantum processors. These advancements are expected to enable the solution of complex computational problems beyond the capabilities of classical computers, driving innovation in cryptography, optimization, and artificial intelligence.

Quantum Communication. The white paper highlights the role of diamond-based systems in advancing quantum communication. The intrinsic properties of diamond NV centers enable secure data transmission through quantum key distribution (QKD), which is particularly critical for sectors such as finance, government, and defense.

Quantum Sensing. NV centers in diamond offer exceptional sensitivity to magnetic and electric fields, temperature, and pressure. These properties enable breakthroughs in medical diagnostics, materials science, and geophysics. Quantum sensors based on diamond technology promise unprecedented accuracy and non-invasive measurement capabilities across a wide range of applications.

Sectors and Use-cases. The white paper identifies key sectors that stand to benefit from Diamond Quantum Technology across quantum sensing, quantum communication, and quantum computing. These include **healthcare**, where diamond-based quantum sensors enable enhanced imaging and diagnostics and quantum computing supports data-intensive analysis and modeling; **finance**, which benefits from secure quantum communication as well as quantum computing approaches for optimization, risk analysis, and fraud detection; **defense**, combining advanced sensing, secure communication, and edge-deployable quantum computing for navigation, signal processing, and decision support; **environmental monitoring**, where high-sensitivity sensors support pollution control and resource management; and **materials science**, which leverages both precise quantum sensing tools and diamond-based quantum computing platforms for simulation, characterization, and accelerated research and development.

Market Potential. The document concludes with an analysis of the market potential for Diamond Quantum Technology. Driven by its relevance across multiple sectors and its ability to address high-impact use cases, the technology is expected to see increasing adoption and market activity over the coming years. The white paper discusses current market trends, potential revenue streams, and investment opportunities, providing a roadmap for stakeholders seeking to engage with the development and commercialization of Diamond Quantum Technology.

This white paper arrives at the following **key recommendations**:

- **Raise Public Awareness**
  Launch awareness campaigns to inform the public and potential stakeholders about the benefits and transformative potential of Diamond Quantum Technology, thereby driving interest and investment.
- **Engage with Policymakers**
  Work closely with policymakers to establish a supportive regulatory environment that facilitates the development and commercialization of diamond quantum technologies.
- **Increase Funding for Research and Development**
  Allocate additional resources to accelerate the progress of Diamond Quantum Technology research, with a focus on overcoming current technical challenges and enhancing NV center capabilities.
- **Establish Industry Standards**
  Develop and adopt a common language and set of standards for the Diamond Quantum Technology community to ensure interoperability and facilitate collaboration among researchers, developers, and manufacturers.

- **Promote Cross-sector Collaboration**
  Encourage partnerships between academia, industry, and government to drive innovation and practical applications of Diamond Quantum Technology across sectors.
- **Invest in Education and Training**
  Support educational initiatives and training programs to build a skilled workforce capable of advancing and deploying Diamond Quantum Technologies.
- **Create Pilot Programs and Testbeds**
  Implement pilot projects and testbeds to demonstrate the practical benefits and capabilities of Diamond Quantum Technology in real-world scenarios, fostering early adoption and market confidence.

In summary, Diamond Quantum Technology represents a significant leap forward in the quantum realm, promising to revolutionize various industries with its unparalleled capabilities. This white paper provides a structured overview of the technology’s potential, outlining its applications, benefits, and market prospects.

Contents

Imprint

This position paper was developed by the following main authors in close consultation with the QBN Members.

Wolfgang Benz, Quantum Brilliance
Jessica Bousquet, DiamFab
David Collomb, Quantum Brilliance
Philipp D'astolfo, Fraunhofer IAF
Felipe Favaro de Oliveira, Qnami
Haissam Hanafi, QBN – Quantum Business Network
Jan Jeske, Fraunhofer IAF
Johannes Lang, Diatope
Matthew Markham, Element Six
Gabriel Puebla-Hellmann, QZabre
Nicole Raatz, SaxonQ
Florentin Reiter, Fraunhofer IAF
David Roy-Guay, SBQuantum
Johannes Verst, QBN – Quantum Business Network

QBN is the global industry network for quantum technologies promoting commercialization, collaboration and the trialogue between industry, science, and policy, and actively drives the industrial adoption and deployment of quantum technologies in Germany, Europe, and worldwide.

Founded in 2020, QBN, represents over 100 international members across the entire value chain, incl. world-leading startups, enterprises, RTOs, investors, and governmental organisations, developing and using quantum technologies, including quantum computing, quantum sensing, quantum communication, and quantum cybersecurity.

QBN builds the industrial quantum powerhouse, driving national security, technological sovereignty, economic growth and a sustainable future.
From Germany to Europe and worldwide - Together we build a resilient Quantum Economy!

Contact
Dipl.-Phys. Johannes Verst
Quantum Business Network UG (haftungsbeschränkt)
Fuerkhofstr. 9, 81927 Munich, Germany
contact@qbn.world, www.qbn.world

Publication

Diamond Quantum Technologies

Synthetic diamond and atom-sized defects in its crystal, so-called color centers, have great potential for applications in quantum computing, quantum communications, and quantum sensing and imaging. Artificial diamond is historically known for its hardness with a broad range of applications in the tooling, cutting and drilling industries. Here, the mechanical properties of diamond are key, whereas for applications in power electronics as efficient heat sinks, the outstanding thermal conductivity of diamond makes it very attractive in the semiconductor industry, where transistor densities in processor chips and the associated heat generation increase drastically.

In quantum technological applications of synthetic diamond, however, the diamond matrix serves as a host for crystallographic defects. Ultrapure diamond material, which can be manufactured using specialized equipment, is essentially free from impurities and thus provides a highly suitable platform for functionalization. Impurities in the crystal structure give diamonds their various colorations, including for example yellow (nitrogen impurities), blue (vacancies) or red to purple (nitrogen vacancy centers).

The latter is a defect that has attracted significant attention over the last two decades due to its outstanding optical and spin properties. Formed by a substitutional nitrogen and an adjacent vacancy, the NV center has an electron spin which can be coherently manipulated at room temperature using microwave radiation applied to this unique quantum system. Additionally, the spin state can be initialized and read out optically. This opens the way to many applications in quantum metrology[1], sensing[2], simulation[3] and quantum computing[4].

While the diamond host matrix makes it robust against external influences, it enables some of the longest coherence times among solid-state spin systems[5]. At the same time, its sensitivity to, for example, extremely weak magnetic fields makes it a highly effective sensor for applications in biomedical analysis and imaging, geology, and the electronics industry. Precise control over the diamond composition at the nanoscale, combined with efficient creation techniques for color centers such as the NV or silicon vacancy (SiV) center, is key to unlocking the applications mentioned above.

In the following, the individual fields of application for diamond based quantum technologies and their color centers are outlined in more detail, providing a comprehensive overview of the current status of this technology, key application areas, opportunities, challenges, and recommendations to further support and leverage it, with the goal of creating novel products that address real world problems and deliver significant benefits to science, the economy, and society. Figure **1** complements this overview by providing an indicative mapping of diamond based quantum applications according to their expected time to impact and disruptive potential across sensing, communication, and computing.

---

[1] Chen et al., "Quantum Metrology with Single Spins in Diamond under Ambient Conditions."
[2] Schmitt et al., "Submillihertz Magnetic Spectroscopy Performed with a Nanoscale Quantum Sensor."
[3] Unden et al., "Coherent Control of Solid State Nuclear Spin Nano-Ensembles."
[4] Abobeih et al., "Fault-Tolerant Operation of a Logical Qubit in a Diamond Quantum Processor."
[5] Balasubramanian et al., "Ultralong Spin Coherence Time in Isotopically Engineered Diamond."

Application Landscape and Disruption Potential of Diamond Quantum Technologies

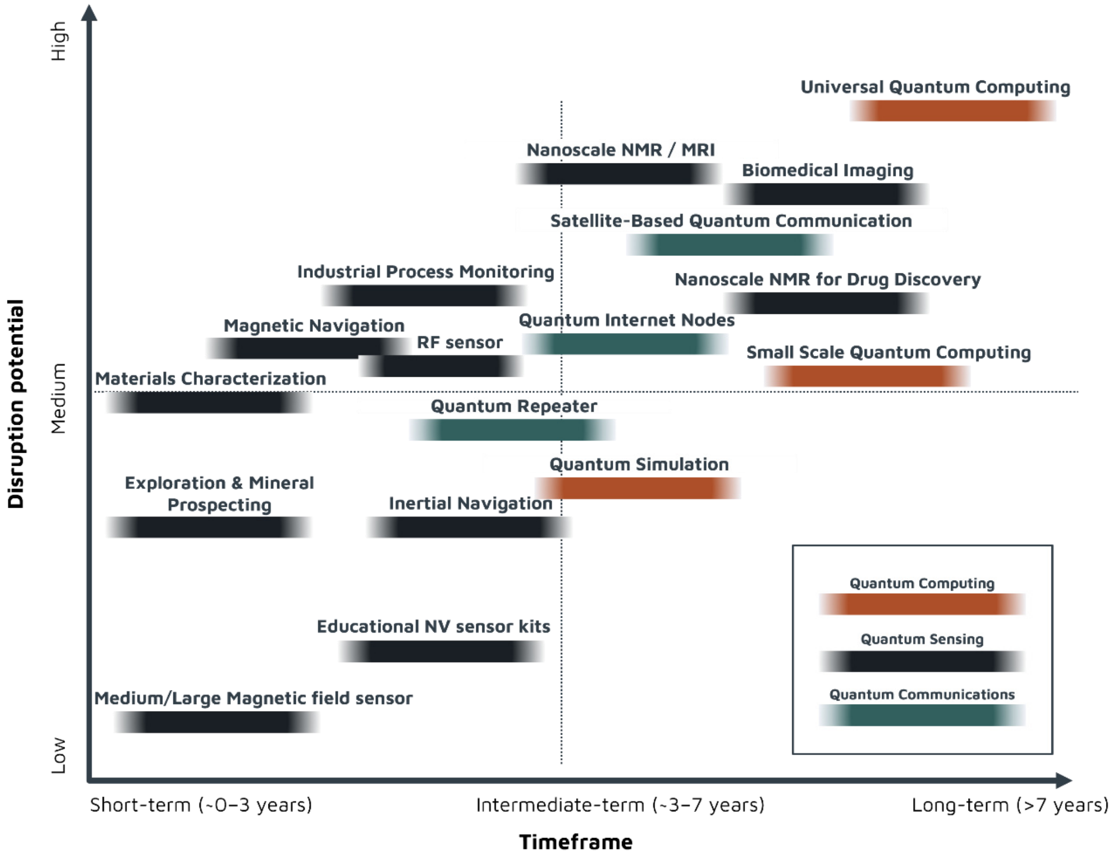

Figure 1: Indicative mapping of diamond-based quantum applications by expected time-to-impact and disruptive potential.

Quantum Computing

Quantum Computing (QC) has the potential to revolutionize the computing industry in the foreseeable future. In particular, gate-based quantum computing also known as digital or universal quantum computing have gained attention over the past decade, due to rapid technological improvements. Among the most promising application areas for quantum computing are optimization tasks in finance, logistics and supply chains, material design, drug discovery, and emerging fields such as Quantum Machine Learning (QML).

The quantum algorithms that aim to solve combinatorial optimization problems exploit superposition to represent all possible solutions to a problem. By exploiting the quantum phenomenon known as entanglement and by cleverly mapping the cost function to the evolution of the quantum system one aims to single out the optimal solution.

Existing classical computing methods for the simulation of molecules and solid-state materials rely on approximations to remain tractable within practical limits on computation time and memory, which constrains achievable accuracy. A quantum computer representing a controllable quantum system may outperform classical computing via increased accuracy, precision and efficiency.

Recent advances in QML showed that quantum computers could achieve a similar performance as classical counterparts on toy problems requiring less training data, which is typically scarce in most industrial applications.

However, today's quantum computers, commonly referred to as noisy intermediate-scale quantum (NISQ) devices, offer only a limited number of qubits and can perform only a restricted number of operations due to noise and limited coherence. To operate within these constraints, variational quantum algorithms have been developed that exploit hybrid quantum-classical workflows. These algorithms leverage the large computational state space of quantum systems to encode problem instances efficiently, while relying on classical optimization routines for parameter updates.

In addition, techniques such as circuit cutting and entanglement forging have been introduced to reduce the effective resource requirements of quantum circuits. While these approaches lower the number of physical qubits required, they typically increase the number of circuit executions, referred to as shots. This leads to longer total runtimes and increased classical post-processing overhead when compared to fully fault-tolerant quantum algorithms such as Grover's algorithm or quantum phase estimation, which rely on error-corrected qubits.
As a result, NISQ-era algorithms can benefit from the parallelized execution of quantum circuits across distributed quantum processors. Their intrinsically hybrid nature also places strong demands on tight integration between quantum hardware and classical computing infrastructure, particularly for control, optimization, and error mitigation.

At the same time, it is important to note that diamond-based quantum technologies are not inherently limited to NISQ operation. Diamond quantum registers that combine electronic and nuclear spins in well-defined coupling topologies offer promising pathways toward quantum error correction. In particular, multi-spin registers with star-like architectures are well suited for encoding logical qubits and implementing error correction codes, positioning diamond-based platforms as candidates for both near-term hybrid quantum computing and longer-term fault-tolerant architectures.

For the time being, diamond quantum computing mostly relies on the nitrogen-vacancy center that has well-defined fluorescence properties, millisecond electronic lifetimes that can be extended up to seconds using decoupling techniques, and nuclear spin resources that have lifetimes up to several minutes.
The key advantages of diamond-based quantum computing over alternative hardware platforms are the potential for room temperature operation, and the potential for miniaturization through the development of integrated devices. In addition, the qubits are embedded in a solid-state material, unlike atomic platforms such as trapped ions and neutral (Rydberg) atoms. This allows for more robust and hence more mobile implementation.

Finally, other quantum computing platforms (e.g., superconducting circuits, trapped ions or neutral atoms) often require a large power budget, low temperature cooling, and extreme environmental isolation.

Scaling Diamond Based QC

In order to scale up diamond-based quantum computers, it is of paramount importance to ensure the availability of both high-precision and deterministic manufacturing processes for NV centers. Ion implantation is utilized to implant nitrogen ions into the diamond crystal, which then undergo a subsequent annealing process, during which NV centers are formed. These NV centers ideally reside in a "magnetic vacuum" of isotopically enriched diamond material, thus shielding them from 13C nuclear spin noise of the diamond matrix. Nuclear-spin-free 12C enriched CVD (chemical vapor deposition) grown diamond layers can be produced reliably and with nanoscale precision.

The combination of CVD diamond growth with NV creation is a powerful tool to precisely control the spatial position of the spin qubit system.[6] In addition to ultrapure diamond growth, doping of the diamond with donors such as for example, sulfur or phosphorus can ensure that the implanted nitrogen atom converts to a stable NV center with enhanced coherence time during the subsequent annealing step.[7] Since a single NV centers does not represent a physical qubit of a future diamond based quantum computer, several approaches are being developed to create qubit registers. These complex spin systems can either involve several coupled NV centers or exhibit coupling of NV centers to isotopically controlled diamond material with 13C nuclear spins. In the case of NV qubit registers, novel fabrication methods are currently deployed to create pairs of NV centers via ion implantation or in combination with CVD diamond overgrowth. In this approach, scaling of the NV qubits is achieved via controlled positioning of several NV centers close enough to exhibit electronic spin coupling. Another approach utilizes 13C nuclear spin close to NV centers to realize NV based qubit registers, where a network of up to 50 13C spin qubits were successfully identified already.[8] To further increase reliability and reproducibility of this approach, the NV centers can be created in a well-controlled matrix of these nuclear spins. This is achieved by CVD diamond growth with precise control on the isotopic concentration of 13C and grown layer thickness an the nanoscale.

A combination of both approaches can then be utilized to enable efficient error correction of the spin qubits, where each of the NV centers couples to a subsystem of 13C nuclear spins, thereby further enhancing the performance and computing power of future diamond-based quantum computers.

In addition to optimization of NV and 13C nuclear spin fabrication techniques, photonic integration can further support the scaling of diamond qubits. Lithography methods already allow for nanostructuring of the diamond surface, including the creation of photonic cavities that significantly enhance the optical properties of NV spin qubits. With NV centers successfully created within optical cavities and optical waveguides fabricated directly on the diamond chip, efficient coupling of distant NV centers may become achievable and could serve as an alternative route toward scaling diamond-based qubit registers.

Another approach to scale diamond-based QC is through combining top-down atomic precision lithography with bottom-up surface chemistry and diamond CVD growth to

---

[6] Findler et al., "Indirect Overgrowth as a Synthesis Route for Superior Diamond Nano Sensors."
[7] Herbschleb et al., "Ultra-Long Coherence Times amongst Room-Temperature Solid-State Spins."
[8] Van De Stolpe et al., "Mapping a 50-Spin-Qubit Network through Correlated Sensing."

enable the deterministic placement of single NV centers in the diamond lattice[9]. This multi-step process is known as Atomic Scale Fabrication (ASF). Figure 2 illustrates how this enables the creation of large arrays of nanometer-proximity NV centers. Here the nuclear spin of the N acts as the qubit and entanglement occurs through the dipolar coupling of the electron spins. A high control of the pitch down to 5 – 10 nm enabling strong dipolar coupling and charge state stability is required in the lithography method. An additional requirement is the lithography precision, or placement accuracy, of ±1 nm. This is spawned from the need to reduce discrepancies in the coupling strengths, and hence control errors in the gate operations, as well as the discrepancies in the magnetic interaction.

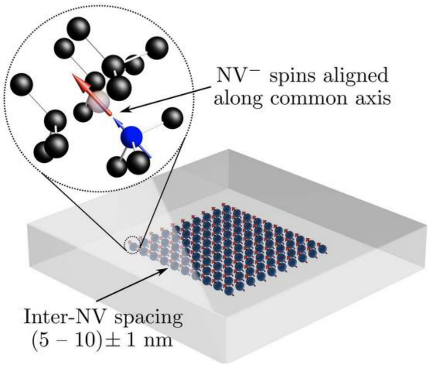

Figure 2: A schematic diagram of a diamond chip with an NV centre square array. The proximity of 5 – 10 nm between NV centres enables a strong dipolar coupling to achieve fast gate operations, while maintaining the desired negative charge state NV centres. (taken from [10])

The ASF process is in fact not novel to diamonds but has been pioneered for silicon quantum devices for several decades[11]. The first step in the ASF process is to terminate the surface of the diamond with hydrogen. This monolayer of covalently bound hydrogen acts like a conventional micro-nano-fabrication resist. The selective removal of individual atoms in the hydrogen resist with atomic precision may then performed by scanning probe lithography, specifically using an atomic resolution scanning tunneling microscope. Removing hydrogen atoms from the surface leaves behind highly chemically reactive dangling bonds at the surface carbon atoms. This process is commonly known as Hydrogen Depassivation Lithography (HDL). Multiple sub-nanometer sized dangling bond patches (groups of adjacent dangling bonds) can be created with sub-nanometer precison and at the desired pitches of 5 – 10 nm. Once the desired array of reactive dangling bond patches are created, the surface can be dosed with a nitrogen containing molecule pre-cursor. This molecule is chosen such that it will selectively covalently bind with the surface at the HDL created patches but will not react with the still hydrogen terminated surface. This surface is then overgrown with diamond using CVD to encapsulate the Nitrogen and incorporate it into the diamond lattice and forming an NV center, courtesy of the high chemical stability of the nitrogen's lone pair[12]. This finally yielding an NV center qubit array in diamond. Figure 3 outlines the entire process flow[9].

---

[9] Oberg et al., "Bottom-up fabrication of scalable room-temperature diamond quantum computing and sensing technologies"
[10] Oberg et al., "Atom-scale fabrication and applications of diamond quantum devices"
[11] Simmons et al., "Towards the atomic-scale fabrication of a silicon-based solid state quantum computer"
[12] Miyazaki et al. "Atomistic mechanism of perfect alignment of nitrogen-vacancy centers in diamond"

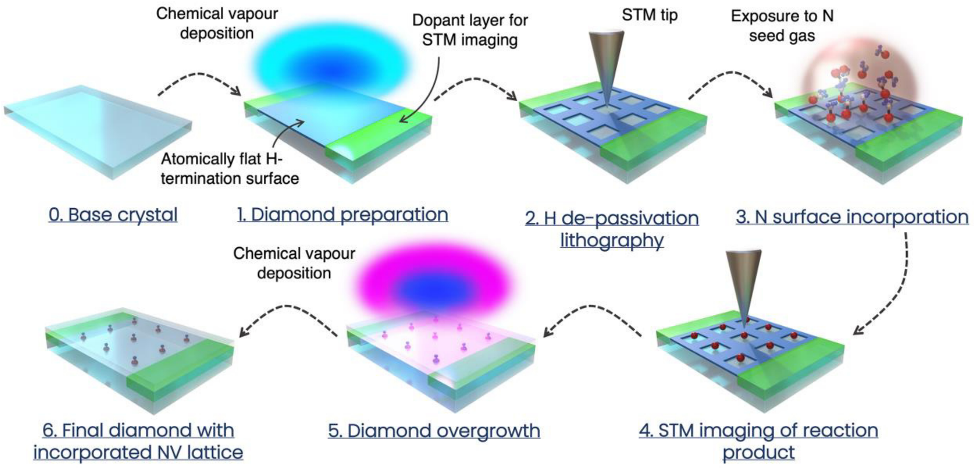

Figure 3: High level process flow for the atom scale fabrication of diamond quantum devices. (0) Starting with a mono-crystalline (111) oriented diamond substrate with no to little background luminescent defects. (1) The creation of the monolayer hydrogen "resist" via for example a CVD plasma process. (2) the Hydrogen Depassivation Lithography performed for example via scanning probe lithography. (3) Dosing of the nitrogen containing precursor to the prepared surface. (4) Process control of steps 2-3 via for example scanning tunnelling microscopy. (5) CVD diamond overgrowth for the incorporation of N and conversion of N to NV centres. (6) finished product with deterministically positioned NV centre array. (taken from [9])

While this process sounds promising as a pathway to fully unlock diamond-based QC, there are still key challenges to be overcome before reaching its potential. Although HDL has been demonstrated on both silicon and diamond, a major challenge is in addressing the scalability issues of the scanning tunneling microscope-based lithography method. In particular, the slower write-based lithography nature, as well as the instability of the tip leading to inconsistencies in the lithographic process are major bottlenecks. Another challenge is in achieving a high retention rate of Nitrogen during the highly volatile CVD diamond overgrowth, in addition to maximizing the N-to-NV conversion ratio.

Applications for NV Center-Based Quantum Computing

The mass deployment of such miniaturized quantum computers will propel industries to harness edge QC applications, and the massive parallelization of quantum computers in next-generation supercomputers. As a result, quantum computers based on NV-centers in diamond operating at room temperature have the potential to become a future addition to the heterogeneous landscape of accelerators in high performance computing, alongside CPUs, GPUs, FPGAs, and ASICs.

Tight integration in quantum computing is imperative because quantum computations inherently rely on a combination of quantum and classical processing, which requires close coordination between quantum hardware and classical computing systems at multiple operational levels. At the control plane, the synthesis of pulse sequences demands precise, real-time interaction between classical control hardware and quantum processors to ensure accurate gate operations. Effective error mitigation further underscores the need for integration; optimizing and compiling circuits, along with implementing SPAM (State Preparation and Measurement) error correction, requires continuous classical computation to adjust quantum instructions dynamically based on error rates.

Moreover, at the quantum error correction level, the operations require immediate classical processing to modify ongoing quantum computations in real time, thereby maintaining coherence and fidelity. Finally, at the application level, the ingestion of data and the optimization of variational parameters in hybrid algorithms like Variational Quantum Eigensolver (VQE) involve iterative classical-quantum feedback loops. These loops continuously update quantum operations based on classical optimization routines, ensuring convergence towards accurate results. Hence, the inherent interdependence between quantum and classical processes mandates tight integration to harness the full potential of quantum computing.

One of the first deployment areas for quantum computing is believed to be in supercomputing centers. Several companies have started endeavors to integrate their devices in high-performance computing (HPC) centers. For example, IQM has partnered with the Leibniz Supercomputing Centre (LRZ) in Germany to integrate their quantum computers into the HPC environment, facilitating advanced research and hybrid quantum-classical computations.

Diamond-based room-temperature quantum computers have made a significant milestone having been deployed at the Pawsey Supercomputing Centre in Perth, Australia[13,14]. This innovative approach eliminates the need for cryogenic cooling, making quantum computing more accessible and practical for various applications. Since the installation at Pawsey, Quantum Brilliance has installed its second generation of the room temperature quantum development kit at the Fraunhofer IAF in Germany[15], as well as having installed three parallelized kits at Oak Ridge national laboratory in the USA[16], further advancing the integration of quantum technology into the HPC ecosystem.

The main advantage of miniaturized and quantum accelerators with moderate energy requirements in the HPC context is the prospect for parallelization. By distributing quantum computational tasks across multiple quantum processors, HPC centers may significantly enhance their processing power and efficiency. This parallelization presents a powerful opportunity to maximize the potential of quantum computing, particularly in the NISQ era, where the limitations of current quantum hardware necessitate innovative approaches to harness their capabilities effectively. The benefits of parallelization manifest at various levels, from shot level to algorithm and application levels:

- **Shot Level Parallelization:** Achieving high-accuracy expectation values necessitates the accumulation of extensive statistical data through numerous measurement shots. To optimize this process, one can partition the required measurement shots across multiple quantum accelerators, thereby enabling simultaneous data collection. This parallelization at the shot level expedites the data acquisition phase and mitigates the impact of individual qubit decoherence, enhancing the overall reliability and precision of the quantum computation.

---

[13] https://www.innovationaus.com/quantum-brilliance-installs-world-first-system-at-pawsey/ (Accessed: 19 January 2026)
[14] Herrmann et al., "First quantum machine learning applications on an on-site room-temperature quantum computer"
[15] https://www.iaf.fraunhofer.de/en/media-library/press-releases/first-room-temperature-quantum-accelerator-in-europe.html (Accessed: 19 January 2026)
[16] https://www.olcf.ornl.gov/2025/09/02/quantum-brilliance-ornl-pioneer-quantum-classical-hybrid-computing/ (Accessed: 19 January 2026)

- **Algorithm Level Parallelization:** For optimization algorithms tackling complex problems, the cost function often comprises diverse contributions that can be independently computed. In molecular simulations, for example, different Pauli terms contributing to the total energy can be evaluated concurrently on separate quantum accelerators. Similarly, in quantum machine learning (QML), data parallelism allows the distribution of the contributions from various data points to the cost function across multiple quantum processors. This level of parallelization leverages the inherent modularity of the algorithmic structure, significantly reducing computation time and resource overhead.
- **Application Level Parallelization:** At the application level, parallelization can be implemented through a divide-and-conquer strategy. In quantum chemistry, for instance, Quantum Mechanics/Molecular Mechanics (QMMM) methods can be employed, where disconnected quantum regions are computed independently on different clusters of quantum accelerators, circuit cutting and knitting techniques, which decompose large quantum circuits into smaller segments, allow these segments to be executed in parallel. This approach maximizes computational efficiency and scalability across a broad range of applications.

Massively parallelized quantum accelerators offer substantial benefits across a range of applications, significantly enhancing computational efficiency and scalability. In quantum chemistry, variational quantum algorithms (VQAs) like the VQE demand numerous measurement shots to achieve chemical accuracy. This is compounded by the necessity to execute many circuits due to the different Pauli terms contributing to the total energy. Parallelizing these tasks across multiple quantum accelerators accelerates data acquisition and computation, enabling more precise and efficient simulations of molecular systems.

Furthermore, in QML, the ability to distribute large datasets across multiple quantum processors during the training phase is crucial. This data parallelism facilitates the handling of vast amounts of data, accelerating the learning process, and improving the performance of quantum algorithms. By leveraging multiple quantum accelerators, QML models can be trained more efficiently. In particular, during the inference phase, where numerous users may submit requests to cloud-based machine learning services, massively parallelized quantum devices are essential to meet latency and throughput requirements. These devices can handle the high demand for rapid inference, ensuring timely responses and maintaining service quality. Massively parallelized quantum accelerators thus address the scalability challenges in both training and inference, meeting the increasing computational demands of modern machine learning applications.

NV center-based quantum accelerators offer a unique advantage by bridging the gap between supercomputing centers and edge computing, which is critical for making quantum computing more broadly accessible. These room-temperature devices provide the scalability and versatility needed to extend quantum capabilities beyond centralized supercomputing hubs to local edge environments. Such a distributed approach ensures that the computational power and benefits of quantum computing are accessible across various sectors and applications, facilitating real-time processing and decision-making at the edge. This integration of NV center-based quantum accelerators paves the way for widespread and practical utilization of quantum technologies, driving innovation and efficiency across industries. The prospect of QML at the edge in applications such as manufacturing, automotive, aerospace, security, and defense are particularly appealing, as this deployment scenario represents a unique advantage of diamond quantum accelerators. It is especially relevant in situations where data are scarce or cannot be transferred to the cloud for inference due to latency or security constraints. In particular, predictive maintenance use cases, such as anomaly detection, could benefit from improved accuracy.

Potential Application Areas of Quantum Machine Learning at the Edge

Defense: In the defense sector, edge quantum computing can enhance target recognition by rapidly processing and analyzing large volumes of data in real-time, improving the accuracy and speed of identifying potential threats. It can also assist in data cleaning and synthesis, enabling the integration of disparate data sources into coherent intelligence. Moreover, signal processing tasks, crucial for communication and surveillance, can benefit from the superior computational capabilities of quantum devices, enhancing encryption, decryption, and pattern recognition.

Medicine: The medical field can benefit significantly from edge quantum computing, particularly in medical image processing. Quantum algorithms can significantly improve the speed and accuracy of analyzing complex medical images, leading to more reliable diagnostics and treatment planning. This capability is especially important in remote or resource-limited settings, where immediate analysis is crucial for patient care.

Chemistry and Pharmaceuticals: Quantum computing can accelerate the prediction of new chemical compounds and pharmaceutical targets. At the edge, this enables real-time simulations and analysis of chemical interactions, shortening drug discovery and development cycles. Researchers can perform complex computations on-site, allowing for faster iterations and more efficient experimental workflows.

Agriculture: Precision agriculture can leverage edge quantum computing for real-time analysis of environmental data, optimizing irrigation, fertilization, and crop management. This can lead to increased yields, reduced resource usage, and more sustainable farming practices.

Manufacturing: In manufacturing, edge quantum computing can revolutionize predictive maintenance by analyzing sensor data in real-time to predict equipment failures before they occur. Quantum-enhanced algorithms can identify subtle patterns and correlations in the data that classical methods might miss, allowing for more accurate predictions. This proactive approach reduces downtime, extends the lifespan of machinery, and minimizes maintenance costs, thereby improving overall operational efficiency and productivity.

Cybersecurity: The field of cybersecurity stands to benefit significantly from edge quantum computing, particularly through more accurate anomaly detection. Quantum-enhanced machine learning algorithms can analyze network data in real-time, identifying unusual patterns and potential threats with greater precision than classical approaches. This heightened detection capability can help organizations respond to cyber threats more swiftly and effectively, enhancing the security of sensitive information and critical infrastructure.

To date, many challenges remain that need to be addressed before such quantum accelerators can operate in harsh environments and withstand radiation, mechanical stress and vibrations, and temperature variations. Moreover, NISQ algorithms still lack clear proof of a quantum advantage. An interesting path forward might be to abandon the purely digital quantum computing paradigm and develop bespoke, problem-specific hardware and software solutions.

Other Color Centers in Diamond

Besides NV centers, other color centers, such as silicon-vacancy (SiV) and germanium-vacancy (GeV) centers, also present advantages that make them attractive candidates for solid-state qubits in diamond.

SiV centers have optical emission lines with **narrower linewidths**, resulting in more stable and coherent photon emissions. This property is crucial for applications in quantum communication and photonic circuits. They show **reduced spectral diffusion,** leading to more consistent and predictable optical behavior. The SiV center's **inversion symmetry** helps in reducing phonon interactions, making them less sensitive to lattice vibrations and, therefore, brighter and more stable at low temperatures.

GeV centers exhibit properties similar to those of SiV centers. In addition, they feature **high quantum efficiency and brightness**, making them suitable for single-photon sources in quantum information processing. They provide **stable emission properties** with reduced inhomogeneous broadening, which is beneficial for scalable quantum networks.

Although they do not operate at room temperature, both SiV and GeV centers can function effectively at higher temperatures than many alternative cryogenic quantum platforms, such as superconducting qubits, semiconductor-based, and cryogenic atomic systems. Their operating temperature, typically around 10–20 K compared to millikelvin temperatures for other solid-state devices, is advantageous for practical quantum devices. Mobile applications can therefore be achieved using miniaturized cooling appliances.

In summary, while NV centers remain a cornerstone of diamond-based quantum technologies, exploring SiV and GeV centers expands the toolkit for developing more efficient, stable, and scalable quantum systems.

Quantum Communication

Exploiting quantum physics for the transmission of information opens a new range of interesting protocols. The most well-known is Quantum Key Distribution (QKD), which leverages the intrinsic security offered by quantum bits of information (qubits) compared to their classical counterparts.

This security is guaranteed by a fundamental theorem of quantum mechanics, the no-cloning theorem[17], which states that an unknown quantum state cannot be copied perfectly due to the linearity of quantum mechanics. As a result, an eavesdropper cannot duplicate a transmitted qubit without interacting with it. Any such interaction necessarily introduces a disturbance equivalent to a measurement, altering the quantum state and breaking the correlations required for secure key generation. When a quantum channel is used to distribute an encryption key, as in the case of QKD, this disturbance reveals the presence of an eavesdropper and indicates that the communication channel has been compromised[18].

The current approach to transmitting qubits over long distances is to exploit single photons. The qubit can be encoded in one of the photon's degrees of freedom, such as polarization, frequency, or time-bin encoding. Transmission is then performed by exploiting the existing fiber network used for classical communication[19], or by using direct free space links[20].
The no-cloning theorem that guarantees the security imposes a limitation on the distance over which quantum communication can occur. Photons propagating through optical fibers are subject to attenuation, which leads to a gradual loss of the transmitted quantum signal and ultimately destroys the encoded qubit. In standard telecom fibers, attenuation typically lies in the range of about 0.2–0.3 dB per kilometer, depending on the wavelength. This corresponds to transmission losses on the order of 30–50% over a distance of 10 km, meaning that a significant fraction of single photons do not reach the receiver. These losses arise primarily from scattering and, to a lesser extent, absorption processes in the fiber.

In classical communication, such attenuation is compensated by repeater nodes that detect, amplify, and retransmit the signal. In quantum communication, however, this strategy cannot be applied, as copying or amplifying an unknown quantum state is fundamentally prohibited by quantum mechanics.

Quantum repeaters work by propagating quantum entanglement over the network[21], creating a chain of nodes. Longer-range QKD is one example of quantum communication applications enabled by memory-enhanced quantum repeaters. The ability to propagate entanglement over long distances is fundamental for other protocols, such as blind quantum computing, quantum clock synchronization, distributed quantum sensing, and distributed quantum computing. The latter could be the enabling technology to overcome

---

[17] Wootters et al., "A Single Quantum Cannot Be Cloned."
[18] Scarani et al., "The Security of Practical Quantum Key Distribution."
[19] Peev et al., "The SECOQC Quantum Key Distribution Network in Vienna."
[20] Hughes et al., "Practical Free-Space Quantum Key Distribution over 10 Km in Daylight and at Night."
[21] Wehner et al., "Quantum Internet."

the challenges associated with scaling quantum computers beyond a few hundred or thousand qubits.

Diamond defects possess several of the requirements for robust quantum repeaters and end nodes[22,23,24]. The spin of the electron trapped at the defect can be addressed by photons, which offer a direct way of transferring the qubit carried by the single photon onto the electron spin. The qubit stored in the color center can be used as a resource to generate the entanglement with the single photon coming from a second quantum network node, thus propagating the quantum information beyond the practical limit for direct links.

Electron spins are not the only resources in diamond color centers. Nuclear spins can offer even longer coherence times, increasing the success rate of the repeater and, consequently, the achievable bit rate. The main drawback of diamond defects such as the NV or SiV centers is their operating wavelength at 630 nm to 730 nm, which is not suitable for the long-range transmission in standard telecom fiber networks operating at 1300 nm to 1550 nm. Nevertheless, coherent frequency-conversion schemes are available and have been employed with SiV quantum memories in local-area networks, demonstrating a route toward new functionalities of quantum networks using diamond-based repeaters.

---

[22] Bhaskar et al., "Experimental Demonstration of Memory-Enhanced Quantum Communication"
[23] Humphreys et al., "Deterministic Delivery of Remote Entanglement on a Quantum Network"
[24] Ruf et al., "Quantum Networks Based on Color Centers in Diamond."

Quantum Sensing

Sensors have become pervasive in our technological landscape, serving as essential components of modern life. Quantum sensor technology offers a paradigm shift in sensitivity and resolution, surpassing traditional sensors by circumventing fundamental certain physical constraints. Among the platforms harnessing quantum effects, the NV defect in diamond stands out.

NV defects can be easily created by replacing adjacent carbon atoms with a nitrogen atom and a vacancy. These engineered defects capture multiple electrons with remarkably responsive quantum properties, making them ideal for sensing applications[25].

NV-based qubits used in quantum sensing allow for the precise measurement of physical parameters like temperature, magnetic fields, or radio-frequency (RF) sources. These qubits, characterized by electronic, magnetic, or vibrational states, serve as highly sensitive probes for various measurement tasks. NV center sensors, embedded within the diamond lattices, offer remarkable magnetic field sensitivity, enabling precise magnetic sensing through Electron Paramagnetic Resonance (EPR) techniques. They have been used across several length scales, from single atoms[26], over microscopic samples, such as currents in microchips[27], to macroscopic samples such as the heart of a mouse[28]. Measurements are conducted by analysing the fluorescence induced by green laser excitation. The intensity of this fluorescence depends on the quantum state of the NV centres, which in turn is affected by the local magnetic field. Microwave radiation is used to control the NV centres via tailored pulse sequences[29], which can be tuned to make the sensor sensitive to the physical quantity of interest.

As illustrated in Figure 4, NV center based sensors occupy a unique operating regime that combines high sensitivity with the potential for miniaturization and room temperature operation. Compared to technologies such as SQUIDs and atomic vapor cells, NV based approaches offer greater flexibility in sensor size and deployment while avoiding the need for cryogenic infrastructure. In addition, their ability to provide vector magnetic field sensing and intrinsic calibration further distinguishes NV center sensors and makes them particularly attractive for applications requiring spatial resolution, mobility, or integration into compact and autonomous systems. In the following sections, various application areas are introduced to provide a broad overview of the potential of diamond-based quantum sensors.

---

[25] Barry et al., "Sensitivity Optimization for NV-Diamond Magnetometry."
[26] Müller et al., "Nuclear Magnetic Resonance Spectroscopy with Single Spin Sensitivity."
[27] Garsi et al., "Three-Dimensional Imaging of Integrated-Circuit Activity Using Quantum Defects in Diamond."
[28] Arai et al., "Millimetre-Scale Magnetocardiography of Living Rats with Thoracotomy."
[29] Hedrich et al., "Parabolic Diamond Scanning Probes for Single-Spin Magnetic Field Imaging."

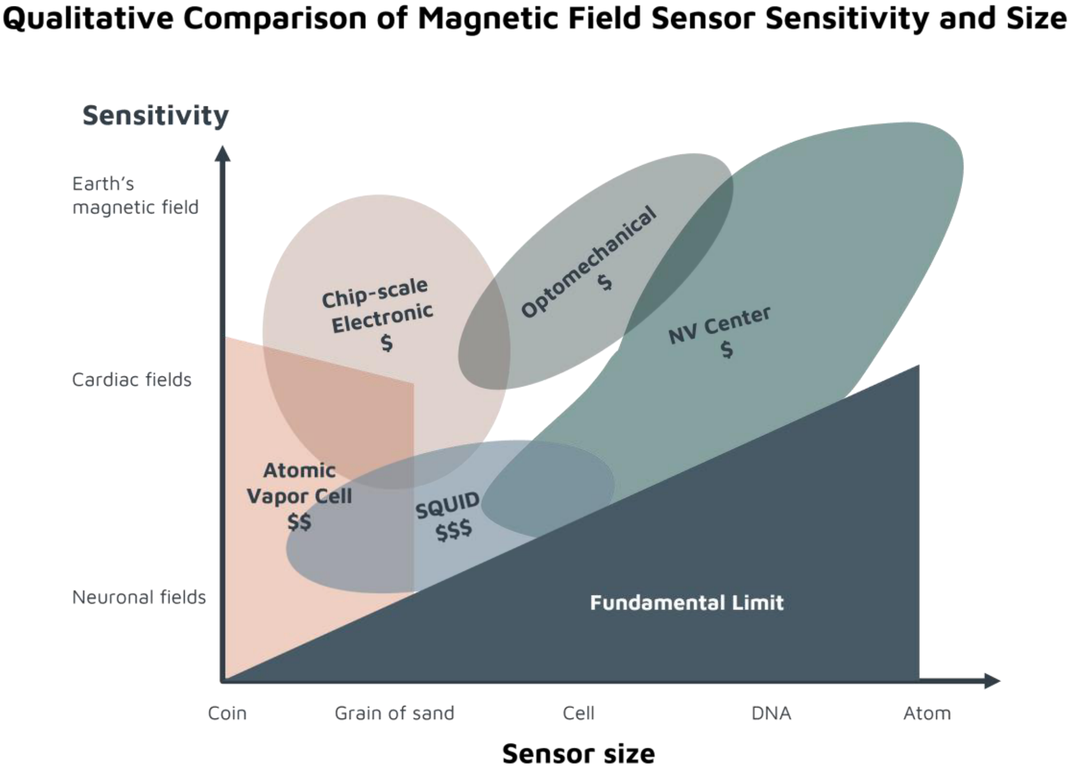

Figure 4: Qualitative comparison of magnetic field sensing technologies. The vertical axis indicates typical magnetic field strengths encountered in real-world scenarios, shown as illustrative reference examples rather than detection limits. The horizontal axis represents typical sensor size and form factor, ranging from laboratory-scale systems to miniaturized devices. The shaded regions indicate approximate operating regimes of different sensor technologies. Dollar symbols denote relative system cost and complexity in a qualitative manner. The figure is intended as a comparative overview and does not represent quantitative performance boundaries.

Nano-Sensing

Scanning magnetometry using a single NV center hosted at the apex of a diamond tip offers unparalleled sensitivity to magnetic fields at the nanoscale, making it a promising tool for various applications such as material characterization. One example where this technology is already impacting is the development and commercialization of spintronics devices like Magnetic Random Access Memory (MRAM) which has gained ground as an alternative to their electronic counterparts[30]. MRAM, a non-volatile memory technology, utilizes spins to store data, offering fast read and write speeds with low power consumption. However, the advancement of MRAM and other spintronic devices requires a fundamental change in the underlying technology of characterization tools as well. While such tools have relied on electric measurements in the past, MRAM devices require a precise characterization tool capable of providing high spatial resolution and quantitative imaging of magnetic properties of the used magnetic materials both at wafer scale, as well as in structured memory bits with sub-100 nm feature sizes.

In this context, diamond-based scanning NV magnetometry (SNVM) becomes vital. Conventional techniques such as magnetic force microscopy (MFM), Magneto-Optical Kerr Effect (MOKE), and Conductive Atomic Force Microscopy (cAFM) may offer limited spatial

---

[30] Dieny et al., "Opportunities and Challenges for Spintronics in the Microelectronic Industry."

resolution, sensitivity and quantitative data, or may be invasive magnetically or electrically. On the other hand, SNVM enables direct and non-perturbing measurements of stray magnetic fields with nanoscale spatial resolution[31,32,33]. NV centers serve as self-calibrated sensors, simplifying the extraction of quantitative data and ensuring the reliability of measurements. This capability is essential for accurately characterizing the magnetic properties of materials used in spintronics devices like MRAM, where precise control and understanding of magnetization at the nanoscale are critical for device performance and optimization[34].

Currently, SNVM has achieved a level of maturity at which commercialization has become a reality. Mapping of magnetic stray fields with sub-50 nm spatial resolution and sensitivities in the range of 1-10 $\mu T/\sqrt{Hz}$ can be routinely achieved. To this end, significant efforts have been directed toward improving scanning diamond sensors, particularly the design of the nanopillar that contains the NV center sensor.[35,36] The developments have yielded devices that direct up to 80% of all emitted light towards the collection optics. Furthermore, measurement protocols focused primarily on enhancing the sensitivity of NV centers to stray magnetic fields[37] have allowed SNVM to break the $\mu T/\sqrt{Hz}$ barrier, which opens the possibility for the detection of even weaker signals or faster measurements without sacrificing the spatial resolution. A different approach, using the motion of the scanning NV sensor to convert gradients into AC signals[38], has enabled 100 $nT/\sqrt{Hz}$ sensitivity, with the option to extend this to sensing electric fields[39]. Using the improved sensitivity in combination with enhanced data processing has enabled real-time extraction of the magnetic field at 10 ms per pixel[40], enabling megapixel resolution images in as little as a few hours.

Beyond material characterization, SNVM promises significant opportunities in the context of signal tracing for failure analysis and circuit verification[41]. The key strengths of high resolution and high sensitivity make it a very useful tool for front-end-of-line development as well as reliability studies and defect localization in test structures. While quality control is an enticing potential application, the significant loss of resolution and complexity of signal analysis due to the typical 10-15 levels of metallization in an integrated circuit may limit the usefulness.

Despite such advances, SNVM still faces challenges and obstacles on the road towards wide adoption as a characterization tool. For instance, in the context of MRAM development, there is a pertinent need for solutions that can accommodate the current bit size of MRAM devices (tens to hundreds of nm), metrology speed (ms measurement per bit) and accuracy of measurements. Further, while SNVM offers exceptional sensitivity and versatility, it

---

[31] Rondin et al., "Magnetometry with Nitrogen-Vacancy Defects in Diamond."
[32] Anderson et al., "Maturation of the Adrenal Medulla--IV. Effects of Morphine."
[33] Degen, "Scanning Magnetic Field Microscope with a Diamond Single-Spin Sensor."
[34] Borràs et al., "A Quantum Sensing Metrology for Magnetic Memories."
[35] Hedrich et al., "Parabolic Diamond Scanning Probes for Single-Spin Magnetic Field Imaging."
[36] Zhu et al., "Multicone Diamond Waveguides for Nanoscale Quantum Sensing."
[37] El-Ella et al., "Optimised Frequency Modulation for Continuous-Wave Optical Magnetic Resonance Sensing Using Nitrogen-Vacancy Ensembles."
[38] Huxter et al., "Scanning Gradiometry with a Single Spin Quantum Magnetometer."
[39] Huxter et al., "Imaging Ferroelectric Domains with a Single-Spin Scanning Quantum Sensor."
[40] Welter et al., "Fast Scanning Nitrogen-Vacancy Magnetometry by Spectrum Demodulation."
[41] Hellmann et al., "Scanning NV Microscopy - Tracing Currents at the Nanometer Scale."

faces challenges when operating under extreme environmental conditions, such as cryogenics or vacuum[42]. To address these challenges, research efforts investigating scanning NV sensors manufactured using different crystallographic orientations[43,44], as well as surface passivation techniques[45] have gained momentum in the past years and could support the widespread use of SNVM as the gold standard in the imaging of magnetic fields at nanoscale.

Magnetic Field Sensing

Known as Magnetic Anomaly Detection (MAD), this fields groups all application domains related to sensing the effect of metallic objects on the Earth's magnetic field. Any metallic or magnetic material will distort Earth's magnetic field lines, revealing its presence to highly sensitive magnetometers. Applications can be categorized as follows: 1) defense, including Anti-Submarine Warfare (ASW), Unexploded Ordnances (UXO) dtection; 2) navigation such as GPS-free navigation, anti-spoofing and jamming technologies, Attitude Determination and Control Systems (ADCS); and 3) exploration in mining.

The key challenge for all these applications is discriminating the signal of interest from the background noise as the signals mix at the location of the sensor. Hence, to fully exploit the accuracy and sensitivity provided by the diamond sensing technology, calibration, magnetic compensation and localization algorithms must be tailored for each use case. One approach to addressing this challenge is the deployment of sensor arrays, either spatially separated or positioned close to magnetic noise sources. As the sensing volume of diamond sensors is very small, their use as drift-free, vector compensation magnetometers could be of great interest.

To increase sensitivity and leverage the properties of the NV centers, large ensembles of NV centers in high density (~ 1 ppm) samples are probed inside a millimeter-sized diamond substrate. Various research groups have demonstrated compact sensing heads with picotesla-range sensitivity, assisted by scientific instrumentation. A few private entities have integrated all the initialization, control, and readout electronics required for vector magnetometry into a single portable instrumentation package. Other key properties of diamond magnetometers include low size, weight, and power (SWaP), the absence of dead zones or heading errors, and a high dynamic range, enabling easy integration into autonomous platforms such as autonomous underwater vehicles (AUVs), unmanned aerial vehicles (UAVs), and other robotic systems.

For each application, key considerations are as follows:

- **Defense**: The primary goal is to detect objects of interest across a wide range sizes and different environments, including underwater, smoke-filled, or camouflage scenarios. Targets range from submarines located up to 1 km below sea level to weapons concealed behind walls. Provided that noise compensation algorithms are implemented, a sensitivity below 10 $pT/\sqrt{Hz}$ at 0.1 Hz is desired. Low SWaP

---

[42] Neethirajan et al., "Controlled Surface Modification to Revive Shallow NV⁻ Centers."
[43] Rohner et al., "(111)-Oriented, Single Crystal Diamond Tips for Nanoscale Scanning Probe Imaging of out-of-Plane Magnetic Fields."
[44] Welter et al., "Scanning Nitrogen-Vacancy Center Magnetometry in Large in-Plane Magnetic Fields."
[45] Kumar et al., "Stability of near Surface Nitrogen Vacancy Centers Using Dielectric Surface Passivation."

requirements (<1000 cm^3, <0.5 kg, <2W) and vector measurement capability are critical for deployment by troops and small autonomous vehicles.

- **Navigation:** Although demonstrations of magnetic navigation have been achieved using total-field magnetometers, access to the vector components provides additional information to improve navigational accuracy[46]. For this use case, a drift less than 100 pT per year is required to surpass classical fluxgate technology. Integration with inertial navigation systems and ADCS used in submarines, vehicles, troops and satellites is desirable, as magnetometers are typically used in conjunction with other sensors.
- **Mining and Exploration:** The net-zero transition and the emerging critical-minerals era are driving increased global exploration spending. One of the first non-invasive airborne sensing methods deployed is magnetic field sensing, primarily for total-field measurements. By building arrays of vector magnetometers, up to nine times more maps can be generated, enabling higher-resolution and three-dimensional imaging of geological structures associated with cobalt and other critical minerals for batteries and renewable energy technologies. Similar SQUID-based systems already in use are incompatible with drone-based surveys. Diamond-based technology provides a room-temperature alternative that can accelerate mineral discovery.

Widefield Magnetic Sensing

The adaptability of the experimental setup and measurement protocols enables NV-diamond magnetic imaging to cater to diverse applications across various research fields. While specific requirements vary between applications, common needs include high sensitivity to magnetic fields within a specified frequency range, fast measurement times, precise spatial resolution, a large field of view, accurate vector magnetometry, and versatility in adjusting the bias field and temperature during measurements.

For instance, magnetic imaging in cell biology typically demands high sensitivity to constant magnetic fields, sub-micrometer spatial resolution, and operation at a constant (room) temperature. On the other hand, microelectronics magnetic field imaging may require sensitivity to magnetic field frequencies reaching into the GHz range, with resolution requirements ranging from tens of nanometers to millimeters[47].

One solution to address these needs in an elegant fashion is wide-field magnetometry. At its core, this technique employs an optical microscope and a camera to detect the fluorescence emitted by a thin layer of ensemble NV centers on the surface of a diamond sensor chip, ranging from a few nanometers to several micrometers in thickness[48]. The sample is positioned as close as possible, often in direct contact with the diamond, allowing the local magnetic field of the sample to be recorded by each pixel of the camera. Subsequently, a comprehensive map of the magnetic field across the wide field of view is generated using the pixel array.

---

[46] Canciani et al. "Absolute Positioning Using the Earth's Magnetic Anomaly Field."

[47] Scholten et al., "Widefield Quantum Microscopy with Nitrogen-Vacancy Centers in Diamond."

[48] Allert et al., "Advances in Nano- and Microscale NMR Spectroscopy Using Diamond Quantum Sensors."

This approach enables the measurement of magnetic field dynamics as well as rapid image acquisition with a large field of view and lateral resolution of up to ~500 nm, limited by optical diffraction. The sensitivity and speed of data collection are limited by the specific configuration of the diamond sensor and camera system in use, whereby measurements can be performed in well under a second under optimized conditions.

Through appropriate optimization, NV-diamond magnetometry can offer combinations of the aforementioned capabilities that are not achievable alternative magnetic imaging techniques. For example, the superconducting quantum interference device (SQUID) microscope, when operating at room temperature, can achieve spatial resolution no better than >150 μm, albeit with exceptional DC-field sensitivity. Conversely, while the magnetic force microscope (MFM) provides superior spatial resolution, it is constrained by small fields of view (<100 μm), limited DC-field resolution (>10 μT), and potential complexities arising from sensor-sample interactions. Moreover, techniques such as the magneto-optical Kerr effect (MOKE) and other Faraday-effect-based magneto-optical imaging methods lack the ability to measure the vectorial components of the magnetic field[49].

As with all magnetic imaging techniques, one of the major drawbacks is the magnetic resolution, which is highly dependent on the standoff. The greater the distance between the NV-ensemble and the sample under investigation, the lower the achievable resolution. In addition, particularly when investigating alternating magnetic fields at higher frequencies, the cost of a high-performance setup can become prohibitive. This is due to the need for high-performance components such as class IV lasers, microwave sources and cameras.

RF Sensing

Current RF sensors tend to be narrowband and therefore have applications only where signals are known and fixed in frequency. RF sensors based on diamond offer the ability to deliver room-temperature operation, low size, weight, and power (SWaP), large instantaneous bandwidths of several gigahertz, and high temporal resolution

Potentially, a device such as this can be deployed to provide real-time cartography of the RF signal frequencies in communication cellular networks, enabling self-optimizing networks (S.O.N.) and thereby increasing network capacity while lowering energy consumption. It can also contribute to the security, reliability, and availability of such networks by detecting jamming and interferences in real-time. This capability is of utmost importance, as demonstrated recently by a potential interference between 5G and air traffic control communications, which may endanger passenger security.

In addition, RF spectrum analysis is of increasing importance for radio astronomy, RF device testing, and is of particular interest to defense organizations. An RF sensor offering large instantaneous bandwidth and high temporal resolution is especially valuable in scenarios

---

[49] Levine et al., "Principles and Techniques of the Quantum Diamond Microscope."

where modern RF systems evade detection by narrowband sensors through frequency hopping irregular pulsed transmission.

Besides diamond-based RF sensors, alternative technologies such as Rydberg atoms offer the capability to sense RF signals with sensitivities greater than those typically achieved by NV-based systems[50]. However, their instantaneous bandwidth remains limited, and coverage of frequency ranges from 0 to 20 GHz typically requires sequential frequency scanning[51]. Achieving broadband operation therefore relies on additional bulky components, which significantly increase SWaP[52].

Several technical challenges for diamond-based RF sensors are readily addressable and include improving the excitation of defects within the diamond to achieve greater uniformity. In addition, the diamond substrate typically used is commercially available and has not been optimized for RF sensing. Employing alternative magnet arrangements could lead to improved instantaneous and total bandwidth while maintaining a relatively high spatial resolution at higher frequencies. Further work is required to determine the ultimate limits of sensitivity and achievable temporal resolution for an optimized RF sensor.

Current diamond-based RF systems rely on detecting the photons emitted by the defects to sense the RF field. However, significant improvements in both SWaP and detection performance could be achieved by measuring the charge instead[53]. It is envisioned that further technological developments could enable allow instantaneous bandwidths exceeding 10 GHz, temporal resolution on the order of 10-100 microseconds, and dynamic ranges of up to 40 dB.

Laser threshold magnetometry

Laser threshold magnetometry (LTM) is based on using NV centers in diamond as a laser medium and performing magnetic field measurements via stimulated emission instead of photoluminescence of NV centers[54]. Using the stimulated (laser) emission of the NV center as a detection signal has the potential to significantly improve sensitivity to magnetic fields.

Highly sensitive magnetic field quantum sensors are increasingly important in various fields, ranging from the mining industry, where they support geological exploration of magnetic minerals, to the defense sector, where they are used for magnetic anomaly detection, as well as for fundamental studies of magnetism. In the medical sector, detecting magnetic fields instead of electric signals provides more precise signals for diagnostics. Unlike electric fields, magnetic fields penetrate bones and skin undistorted. These magnetic signatures can serve as ideal signals, for example, to precisely control prostheses through nerve signals or even brain activity via so-called brain-computer interfaces (BCIs). Magnetic field signals from the human brain can currently only be detected by SQUIDs and optically pumped magnetometers (OPMs), reaching sensitivities in the $fT/\sqrt{Hz}$ regime. However, these technologies require operation in extreme conditions. SQUIDs require

---

[50] Fancher et al., "Rydberg Atom Electric Field Sensors for Communications and Sensing."
[51] Meyer et al., "Waveguide-coupled Rydberg spectrum analyzer from 0 to 20 GHz
[52] Zhang et al., "Quantum Scaling Atomic Superheterodyne Receiver."
[53] Bourgeois et al., "Photoelectric Detection of Nitrogen-Vacancy Centers Magnetic Resonances in Diamond."
[54] Jeske et al., "Laser Threshold Magnetometry.'"

cryogenic cooling with liquid helium, while OPM technology requires a zero-magnetic-field environment and heating above 100°C to create the atomic vapor.

Collecting the photoluminescence of the NV centers is a well-established and widely used technique for measuring the magnetic fields at room temperature, offering a large dynamic range even in the presence of the Earth's magnetic field. Currently, the sensitivity of photoluminescence-based NV magnetometers operated in background magnetic fields reaches the single-digit $pT/\sqrt{Hz}$ regime. Theoretical considerations have shown that LTM could achieve sensitivities in the single-digit $fT/\sqrt{Hz}$ range, thereby entering sensitivity regime of SQUID and OPM sensors while retaining the benefits of NV-based sensing under ambient conditions.

The improved magnetic-field sensitivity of LTM arises from two main effects. On the one hand, the collection efficiency of a collimated laser beam is higher, leading to stronger signals and improved signal-to-noise ratio. On the other hand, small changes in the brightness of the stimulated emission induced by the magnetic field are intrinsically amplified by the laser cavity, resulting in much higher contrasts in the detection signal. At the same time, LTM offers a large dynamic range that enables sensing in the presence of substantial background fields, such as Earth's magnetic field.

Since its publication in 2016, the concept of LTM has attracted great attention, and further approaches to realize LTM have been proposed [55,56,57]. The first magnetic-field-dependent light amplification measurement demonstrated a record contrast of more than 30%, corresponding to a strong magnetic-field-induced modulation of the stimulated emission output from NV center ensembles. The fact that this contrast, amplified by an optical cavity, exceeds the fluorescence contrast demonstrates the principle of laser threshold magnetometry for the first time. Furthermore, the first two-media continuous wave NV laser system with laser threshold was successfully realized[58], and LTM on the NV infrared-transition was shown. Despite a first demonstrated shot-noise limited sensitivity of 30 $pT/\sqrt{Hz}$[59], current sensitivities are limited to 7.5 $nT/\sqrt{Hz}$ [60]. Reducing technical and laser noise remains challenging, and further material development for high-quality NV-diamond with low optical losses is required.

Diamond Maser

Masers produce a coherent microwave source in the same way as a laser. However, masers predate lasers and, unlike lasers, have found only limited application due to the need for either cryogenic cooling or operation under at vacuum conditions. This has made maser too expensive for widespread use, with newer technologies superseding them in several applications. Unlike other masing technologies, a diamond maser can operate continuously

---

[55] Dumeige et al., "Infrared Laser Threshold Magnetometry with a NV Doped Diamond Intracavity Etalon"

[56] Webb et al., "Laser Threshold Magnetometry Using Green-Light Absorption by Diamond Nitrogen Vacancies in an External Cavity Laser."

[57] Raman Nair et al., "Absorptive Laser Threshold Magnetometry."

[58] Lindner et al. "Dual-media laser system: Nitrogen vacancy diamond and red semiconductor"

[59] Hahl et al. "Magnetic-field-dependent stimulated emission from nitrogen-vacancy centers in diamond"

[60] Gottesman et al., "Infrared vertical external cavity surface emitting laser threshold magnetometer"

at room temperature under ambient conditions and can be tuned to operate at various frequencies[61].

Historically, the most successful application of masers has been hydrogen masers, which have served as the basis for high-precision frequency standards. Masers have also been used as low-noise microwave amplifiers but were eventually replaced by newer, more cost-effective technologies. Several potential applications of a diamond maser include mode cooling, which would allow a reduction of the noise level of systems without the need for expensive and bulky cryogenic equipment[62]. Another potential application is in microwave spectroscopy, which could be used to investigate the dynamics of complex reactions, in particular ongoing chemical reactions, and would would be highly beneficial for evaluating the performance of new catalysts. In addition, microwave spectrometers could also be used in radio telescopes to determine the chemical composition of unknown gases.

The hydrogen maser is a commercially available maser system, which prices typically exceeding USD 200,000. While hydrogen masers are widely used in high-precision atomic clocks, it is unlikely that a diamond maser would match their performance in this application. Another alternative technology is the pentacene-doped p-terphenyl, which operates at room temperature. However, the material is fragile and cannot operate at a continuous wave setting, which severely limits its application. A more recent technology offering performance comparable to diamond-based systems is the silicon-vacancy center in silicon carbide[63], which has demonstrated similar performance for applications such as mode cooling.

Current diamond masers have demonstrated signal amplification of up to two orders of magnitude. However, this performance has so far been achieved at liquid nitrogen temperatures[64], and further work is required to demonstrate amplification at room temperature. In addition, achieving amplification at room temperature with low size, weight, and power (SWaP) remains a development challenge, although it appears promising through optimization of the diamond material and device geometry. Further improvements are expected from the miniaturization of currently required components, such as large bias magnets.

Gyroscopes

A gyroscope is an angular rate sensor that measures or maintains the rotation rate over a sensitive inertial axis. Such inertial sensors are key components for navigation stabilization in air, sea, and land. Several studies have demonstrated that such a rate sensor can be realized in a solid-state system using NV color center in diamond[65,66]. The potential of a

---

[61] Breeze et al., "Continuous-Wave Room-Temperature Diamond Maser."
[62] Zhang et al., "Cavity Quantum Electrodynamics Effects of Optically Cooled Nitrogen-Vacancy Centers Coupled to a High Frequency Microwave Resonator."
[63] Gottscholl et al., "Room-Temperature Silicon Carbide Maser."
[64] Sherman et al., "Diamond-Based Microwave Quantum Amplifier."
[65] Jarmola et al., "Demonstration of Diamond Nuclear Spin Gyroscope."
[66] Soshenko et al., "Nuclear Spin Gyroscope Based on the Nitrogen Vacancy Center in Diamond."

Quantum-Gyroscope Sensor lies in its large scalability and robustness, which are given by the solid-state environment[67].

There is a wide range of potential applications and markets for inertial sensors. In aeronautics and aviation, inertial measurement units rely on gyroscopes to account for changes in direction. By knowing the starting point of a flight and detection all subsequent rotations and accelerations, the current position and orientation of the object can be determined. This requires accelerometers and a three-axis gyroscope. Similarly, in the automotive sector, inertial sensors are required for automated driving to provide feedback on the current position and direction of motion. The navigation of unmanned rockets, satellites and drones can be performed using long-time stabilized gyroscopes.

Typical requirements for such a rotation-rate sensor in so-called short-term navigation are stabilities better than than 0.1°/h[68]. The increase in position error with increasing navigation time is of crucial importance in inertial sensor technology. It is therefore necessary to achieve even higher stability for high-end navigation, down to 0.001°/h. At present, such performances can only be achieved by mechanical or ring laser gyroscopes, which are expensive and/or have a large form factor.

The detection of rotation rates using NV centers is achieved by measuring changes in the red fluorescence of the color centers between the rotated and unrotated system. This change in fluorescence indicates a phase shift in the high order nuclear Ramsey oscillation of the ^{14}N nuclear spin of the NV center, which is coupled to the optical active electron spin of it due to flip flop interactions between the spins in the excited state level and crossing regime[69]. This interaction enables the initialization and readout of the nuclear spin state of the NV center and thus allows the nuclear spin to be used as a sensor. Nuclear spins are preferred for the detection of rotation rates, as they have a significantly smaller magnetic moment and therefore precess more slowly, making rotation easier to detect. This leads to a high sensitivity and a low bias drift of less than 0.01°/h for NMR gyroscopes[70,71].

One of the main disadvantages of conventional gas cell NMR magnetometers lies in the need to shield magnetic stray fields, as these directly change the precession frequencies and thus prevent the highly accurate frequency measurement required for gyroscope applications. Furthermore, gas cells require a high operating temperature (approx. 120 - 140°C), which results in an increased electrical power consumption. To overcome these limitations, NV-doped diamond represents an attractive alternative to the sensor types mentioned above, as NV centers are embedded in an ultra-stable solid-state system and no heating or cooling is required during operation.

---

[67] Passaro et al., "Gyroscope Technology and Applications."
[68] Wood, "High-End Gyroscopes, Accelerometers and IMUs for Defense, Aerospace & Industrial Markets 2015-2019."
[69] Jarmola et al., "Demonstration of Diamond Nuclear Spin Gyroscope."
[70] Meyer et al., "Nuclear Magnetic Resonance Gyro for Inertial Navigation."
[71] Budker et al., *Optical Magnetometry*.

Market Potential

We expect Diamond Quantum Technology to enable the demonstration of intermediate-scale quantum simulator and quantum computer hardware based on spin qubits in the near future.
Developments along these lines are expected within the next few years through advancements in the scalability to larger numbers of qubits, thereby allowing to address problems in simulation and computation tasks based on Diamond Quantum Technology. Material engineering, advanced techniques for control and readout, and algorithm development, will mature diamond-based quantum computers/simulators, and thus lay the ground to scale to where quantum advantages may become apparent. This opens up the possibility of catching up with competing technologies and possibly even surpassing them, thereby opening up new markets.

The advancement of diamond quantum computing and simulation technologies is expected to have a significant impact on technologies and developments in many industries and fields of research. These range from the education sector, where affordable demonstrators for quantum computing are of high interest, through basic research disciplines like chemistry, protein engineering or materials science, to advanced technologies like cryptography. For the latter, due to its impact on secure communication channels, a substantial societal impact is expected if scalable quantum computing platforms based on diamond can be established.
More specifically, diamond quantum simulation and computing platforms offer distinct advantages over currently established qubit technologies. On the one hand, the usage of an optically and electronically addressable defect in a solid-state material provides additional pathways for qubit readout and interconnection. On the other hand, the stable host matrix of diamond enable operation at or near room temperature, which is a distinguishing feature for diamond-based quantum technologies.
Room-temperature operation will drastically reduce the energy demand of quantum computing devices and thereby make a direct contribution to the EU missions towards resource-efficient technologies. Quantum computers operating at or near room temperature will create new business opportunities and applications in distributed, mobile and massively parallelized quantum computing. It is evident from the recently established companies such as Quantum Brilliance, SaxonQ, and XeedQ that industry perceives large market for diamond-based quantum devices.

According to the Quantum Technology Market Research report by GlobeNewswire[72], the overall global quantum technology market will reach USD 42.4 billion by 2027, with quantum computing leading the market to reach USD 16.1 billion, corresponding to a compound annual growth rate (CAGR) of 39.4%. Germany is expected to lead the European quantum technology market at USD 3.6 billion by 2027, with a CAGR of 33.1%.

As of April 2023, according to the Quantum Technology Monitor report by McKinsey[73],the total investment by technology companies and new start-up ventures across various

---

[72] Wood, "Global Quantum Technology Market Research Report 2022-2027: Quantum Dots Market Will Reach $13.25 Billion by 2027, Growing a 25.1% CAGR and Led by Displays."
[73] McKinsey Technology Council, "Quantum Technology Monitor." (April 2023)

quantum hardware platforms amounted to approximately USD 7 billion, with Diamond Quantum Technology accounting for around 4%. This share may increase in light of recent advancements in diamond quantum computing, supported by government-related funding initiatives in this field. The market potential for Diamond Quantum Technology is considerable due to the unique properties of diamond in terms of stability, coherence, and scalability.

Diamond quantum sensors are poised to transform numerous industries by delivering quantum sensing capabilities that surpass conventional limits. This technology leverages the unique properties of NV centers in diamond, enabling highly sensitive and precise measurements of magnetic fields, temperature, and other physical quantities.

Over the next decade, the market for diamond quantum sensors is expected to expand significantly, driven by their potential to revolutionize a wide range of applications.
In navigation, these sensors can enhance positioning accuracy, particularly in environments where GPS signals are weak or unavailable. Timekeeping could benefit from unprecedented precision, improving applications ranging from financial transactions to global communication networks.
In the military and defense sector, applications include the delivering of highly accurate positioning data, submarine detection in the world's oceans, and the detection of RF signals from distant sources.
Similarly, in the automotive industry, these sensors are becoming increasingly relevant due to their ability to provide highly accurate measurements for precision navigation.
Environmental monitoring will also benefit significantly, as diamond quantum sensors can detect subtle changes in the Earth's magnetic field, supporting geological surveys and disaster prevention.
In healthcare, diamond quantum sensors promise breakthroughs in imaging and diagnostics. Their sensitivity can lead to earlier disease detection and more precise imaging techniques, potentially revolutionizing MRI and other diagnostic tools.
In the industrial sector, diamond quantum sensors are expected to improve manufacturing processes, particularly in aerospace, electronics, and automotive industries, by enhancing quality control and reducing defects.
In addition, research and development activities stand to benefit from advances in diamond quantum sensing, enabling new scientific discoveries and technological progress.
European enterprises, with their strong investment in spin-based quantum platforms, are expected to play leading role in adopting these innovations. The rapid uptake of diamond quantum sensors by European companies is likely to accelerate commercialization and further technological developments, reinforcing Europe's position as a leader in this cutting-edge technology.
Diamond quantum sensors are expected to have a substantial impact across multiple industries, from navigation to healthcare, driven by their unprecedented precision and sensitivity. The quantum sensing market[74] is projected to reach USD 989 million[75] globally by 2027, with the Asia-Pacific region representing the largest and fastest-growing market.

---

[74] "Quantum Sensors Market Size & Share Analysis - Growth Trends & Forecasts (2024 - 2029), https://www.Mordorintelligence.Com/Industry-Reports/Quantum-Sensors-Market." (Accessed: 19 January 2026)

[75] Wood, "Global Quantum Technology Market Research Report 2022-2027: Quantum Dots Market Will Reach $13.25 Billion by 2027, Growing a 25.1% CAGR and Led by Displays."

Diamond quantum technology is therefore expected to unlock additional resources for research and innovation and to attract new players from both academia and industry, thereby increasing research activity and contributing to market growth. Similar dynamics have been observed in recent years for neutral-atom (Rydberg) platforms. A scaling to an additional 30 academic groups and 5-10 companies in the EU alone is expected within the next five years, with a projected market of approximately 100 devices, including both simulators and computers, produced withing the same timeframe.

Diamond Quantum Technology - SWOT

Strengths

Quantum technologies based on diamond, such as quantum devices using NV centers, offer several advantages. These will not only make them competitive with more established hardware modalities but may also allow diamond-based quantum devices to outperform previous technologies in the intermediate and longer term. In particular, in mobile, medical, and military applications, diamond quantum technologies hold unique features that create a range of opportunities.

Specifically, in contrast to bulky sensors based on previous technologies, NV-based sensors exploit the atomic size of their elementary sensing unit. Similarly, for quantum computing applications, the NV-center qubit can be realized in a solid-state platform, like a superconducting qubit, while maintaining atomic-scale size comparable to trapped-ion or neutral-atom qubits. Compared to these platforms, however, NV centers require neither cryogenic appliances realizing temperatures close to absolute zero nor vacuum chambers, as required by atomic platforms.

Room-temperature operation, long qubit lifetime, and integration in a solid-state host provides unique robustness against external disturbances. In comparison, superconducting qubits need to be shielded against ambient thermal fluctuations, as well as energetic radiation from space. While being robust, NV center qubits maintain their sensitivity to external signals such as magnetic fields, temperature, and mechanical stress depending on the sensing scheme employed.

Owing also to their efficiency, NV center based quantum technology are inherently mobile, as has been demonstrated and even commercialized by leading players in the field.

The materials constituting the qubit, carbon and nitrogen, are naturally abundant, thus avoiding additional dependencies and enabling stable and resilient supply chains.

The absence of a monopoly in NV-center-based computing and sensing represents a strength of the technology, provided that the various players can communicate and cooperate effectively, postponing direct competition to later stages of maturity. Competition is expected to be less dominant than the targeted pursuit of specific application domains and niches, such as education, mobility, and medical devices. Diamond quantum technology can thus follow the constructive development path observed for other qubit platforms, with a strong and diverse ecosystem jointly driving progress.

Weaknesses

While naturally abundant, a challenge for Diamond Quantum Technology is the availability of artificial diamond as a *synthetic* material. Growth rates as well as wafer sizes are technically limited, and further development is needed to increase them. This issue has already been addressed in dedicated roadmaps[76].

---

[76] For example, for large diamond wafers in the {100} orientation, the diamond producer Orbray aims to increase wafer sizes from 2-inch (today) to 4-inch (in 2025), up to 8 inch (in 2030), with nitrogen densities of below 3 ppb. The producer Diamond Foundry can already produce 4-inch wafers as of today.

Another challenge is the scalability of quantum computing based on NV-centers in diamond. Nitrogen atoms need to be precisely positioned, and NV centers must be formed through annealing processes. This requires deterministic implantation technologies, which have been pioneered at universities but still need to be transferred into a commercial manufacturing context.

In addition, NV qubits need to maintain a stable charge state, which can be addressed through the implantation of additional atomic species, for which several approaches are currently under investigation. While challenges in the deterministic creation of NV qubits are being addressed through large public funding programs, the transfer to industrial-scale production and commercialization will likely require sustained, long-term support to fully realized the potential of diamond-based quantum.
In parallel, standardization of the technology should be actively driven to ensure reproducibility of material quality and qubit properties. This will help overcome reliance on isolated, non-reproducible high-performance samples, on which academic research is still partially based, and will support the transition toward the reliable, large-scale production of diamond quantum devices within a robust value chain.

Opportunities

Diamond quantum technology is emerging from a vibrant start-up community that shares ecosystems for foundry, implantation, and characterization of the qubits. Collaboration with established industries, such as medical technology and navigation, is ongoing and expanding to identify additional application domains.
The underlying physical principles of the technology are well understood, allowing efforts to focus increasingly on engineering challenges rather than fundamental scientific uncertainties.

Threats

A key risk to avoid is falling into a hype trap. Just as the competition between vacuum tubes and transistors in classical computers took decades to resolve, the competition between different qubit modalities should not be expected to be decided quickly in favor of a single approach. Multiple technological pathways must be explored to fully realized the long-term potential of NV-based quantum technologies. In the intermediate term, other technologies may remain more accessible for proof-of-principle demonstrations, in particular in quantum computing.
It is therefore essential that the actual state of the technology is communicated transparently and that overselling is avoided.

The higher visibility of other platforms, such as superconducting qubits and Rydberg-atom sytems (currently reaching on the order of 1000 qubits), should be viewed as a natural part of the technology development process. Funding agencies should be made aware that, for diamond-based technologies, many challenges lie in an earlier stage of development, in contrast to platforms that more readily achieved the first 10–100 qubits but are now increasingly constrained by cryogenic requirements and limited qubit lifetimes.

Conclusion and Recommendations

Quantum diamond technology is rapidly approaching readiness for real-world applications, with significant progress in both quantum computing and sensing. Demonstrations of diamond-based quantum computing systems have proven successful, and quantum sensing solutions have been tested and validated in various real-world environments. This progress is driven by a growing ecosystem of startups and RTOs along the Diamond Quantum Technology value chain, working together to advance innovation in the field.

Recommendations

1. **Support for Pilot Production Lines**
   Establishing pilot lines is essential to streamline base solutions, minimize redundant technology development, and accelerate the commercialization of quantum diamond technologies.
2. **Scaling Diamond to Wafer Level**
   Expanding diamond processing to wafer scales will facilitate easier integration with existing systems, providing a path to enhanced production capacity and broader industry adoption.
3. **Precision Modification for NV Centers**
   Invest in techniques to precisely control NV centers within diamonds, such as through targeted implantation and advanced processing methods for enhanced light extraction.
4. **Quantum Sensing Testbeds**
   Develop testbeds specifically for quantum sensing applications to allow for systematic testing, refinement, and demonstration of quantum sensing capabilities across various scenarios.
5. **Inclusive Platform Development**
   While diamond holds unique potential, other platforms should not be excluded. History shows how complementary technologies (e.g., transistors and vacuum tubes) can coexist and drive innovation.
6. **Unified Terminology and Standards**
   Establish a common language across the quantum diamond sector, from research labs to industry, to bridge gaps between scientists and business stakeholders. Define materials, components, and equipment characteristics needed for quantum sensing, quantum communication, and quantum computing.

Key Areas for Development

- **Diamond Characterization and Standardization**
  Developing standardized methods to characterize diamond materials is critical for quality control and benchmarking across the industry.
- **Advanced Characterization Tools and Techniques**

Invest in state-of-the-art tools that enable precise assessment and manipulation of diamond properties, enhancing device performance.

- **Diamond Processing Compatibility**
  Research processing methods that ensure compatibility with existing fabrication techniques, enabling efficient scaling and integration.
- **Collaborative Research and Development**
  Foster collaboration between academia and industry to drive advancements in modeling, simulation, and software tools, crucial for design and innovation in quantum diamond technologies.
- **Sensitivity and Application-Specific Enhancements**
  Improve sensitivity and tailor diamond quantum technology applications to specific use cases in sensing and communication.

Addressing Key Challenges and Potential Advancements

- **Funding and Prototyping Needs**
  Bridge the funding gap between initial demonstration stages and small-scale prototype development, such as those between the German BMFTR demonstrator phase and subsequent production phases.
- **Advanced Sensing Technologies**
  Address technical challenges in sensing, such as mitigating cross-talk in closely spaced color centers and optimizing nanoscale electrodes to enhance sensitivity and reliability.
- **Improved NV Center Control**
  Enhance control over NV center density, positioning, and properties through the development of high-precision photonic and spin interfacing technologies.
- **Standardization Efforts and Communication Alignment**
  Establish reference measurement techniques and promote a unified language within the sector, ensuring that quantum diamond advancements align with broader technology and industry standards.

With coordinated efforts across these areas, quantum diamond technology can reach its full potential, offering transformative capabilities for industries ranging from defense and communications to environmental monitoring.

Contributing Companies

- **DiamFab**
  Diamfab is an internationally recognized pioneer in semiconductor diamonds. Founded in 2019 and based in Grenoble (France), Diamfab is a spin-off from the Centre National de la Recherche Scientifique (CNRS) headed by Gauthier Chicot, Khaled Driche, Ivan Llaurado and currently employs 15 people. The company synthesizes high value-added diamond wafers for the semiconductor industry. It also designs diamond-based electronic component architectures, and develops the corresponding manufacturing processes. With electrical and thermal performance superior to SiC and GaN, record efficiency, compactness, and a reduced carbon footprint throughout the process (from material manufacture to component use), Diamfab's high value-added diamond wafers are designed to play a major role in the electrification of society. From electric cars to the future high-voltage grid, from hybrid aircraft to batteries for connected objects, diamond will be at the heart of the energy transition.

- **Diatope**
  The German Startup was founded in September 2021 as a spin-off of the Institute of Quantum Optics at Ulm University. The founders around managing directors Christoph Findler, Dr. Johannes Lang (CEO) and Dr. Christian Osterkamp have set themselves the goal of developing and manufacturing artificial diamonds as hardware specifically for applications in quantum sensor technology and quantum computing.
  For the ecosystem of diamond-based quantum technologies, a reliable supply of diamond hardware tailored to the application is crucial in order to transfer this future technology to the market and from the laboratory to the application.
  By establishing the world's first "Made-in-Germany" production line for quantum diamonds and centralizing all necessary processing steps, synthetic diamond material with qubit and sensor properties will be supplied, which is developed and optimized for the respective application.

- **Element Six**
  Element Six (E6), part of the De Beers Group, is a world-leader in the design, development and production of synthetic diamond and tungsten carbide advanced material solutions. The company operates worldwide with primary manufacturing facilities in Germany, Ireland, South Africa, the UK and US.
  Element Six uses the extreme properties of synthetic diamond to open up new possibilities in areas such as quantum technologies, acoustics, power transmission, water treatment, thermal management and sensors. The company's advanced material solutions are used in a wide range of applications across multiple industries including manufacturing in the Automotive and Consumer Electronics industries, cutting and drilling in the Oil & Gas industry, and in components for Mining, Road & Wear applications.

- **Fraunhofer IAF**
  The Fraunhofer Institute for Applied Solid State Physics IAF is a leading research organization in Germany. It focuses on developing innovative semiconductor technologies and materials, especially in the fields of electronics, optoelectronics, and quantum technologies. The institute collaborates with both industry and academia to drive advancements in these areas, aiming to provide practical solutions and foster technological progress. Along these lines, Fraunhofer IAF explores in particular quantum computing and quantum sensing based on color centers in diamond, as well as quantum algorithms research. The institute acts as a key player in these nascent fields, executing and coordinating projects at the state, federal, and European level.

- **SaxonQ**
  The SaxonQ GmbH, founded in 2021, develops and commercializes scalable mobile quantum computers based on NV centers in diamond. The qubits themselves are created through a patented ion implantation fabrication technology which includes Fermi level engineering in the diamond chip. This results in accurate and robust, time-stable qubit arrays from NV centers and neighboring nuclear qubits, paving the way for scalable error-corrected diamond-based quantum computers. The scaling is based on patented structures using direct "dipole-dipole" coupling of NV centers. The qubit control is achieved with microwave structures on the diamond surface and a spin-photon interface. Such quantum computers are freely gate programmable and will be accessible for a wider user community, like research institutions, industries, quantum software developers and even private persons through a cloud-based user interface which is designed to run and test codes or algorithms in real time.

- **SBQuantum**
  Founded and based in the quantum technology hub of Sherbrooke, Canada, SBQuantum is producing leading edge hardware in the field of diamond based quantum sensing, combined with advanced interpretation and compensation algorithms for exploration in mining and aerospace. As part of the MagQuest challenge, its diamond quantum magnetometer has been tested at NASA’s Goddard Space Flight Center for LEO operation. SBQ’s miniaturized sensors have been field deployed and will accelerate adoption of magnetic field sensing on unmanned vehicles for accelerated minerals discovery.

- **Qnami**
  Founded in 2018 with its roots at the University of Basel in Switzerland, Qnami is a global leader and pioneer in the development and commercialization of quantum technologies for sensing and imaging applications. We offer cutting edge scientific instruments and analytical solutions for applications in nanotechnology, life-science and earth science. Our expertise covers the nano-fabrication of diamond quantum chips, system integration and the development of software for data analytics. With this technology, Qnami is redefining the common understanding of precision.

- **Quantum Brilliance**
  Quantum Brilliance (QB) is focused on advancing diamond-based quantum technology and pioneering the development of diamond quantum accelerators that operate at room temperature. Unlike traditional quantum hardware, QB's accelerators do not require cryogenics, vacuum systems, or complex laser arrays, leading to substantially lower energy consumption. This also allows for their deployment in diverse locations, including on-site data centres and in edge devices. Founded in Australia in 2019, QB has expanded globally with operations in Germany, Singapore, and the UK. Today, QB exports globally diamond quantum accelerators, complemented by a range of software and application tools. QB aims to miniaturise its technology to the scale of semiconductor chips, a move that would integrate quantum computing capabilities into everyday devices, expanding the practical applications of quantum computing. Over the past few years, QB has attracted world-leading scientific and commercial talent in Australia and Europe and established more than 25 partnerships with key stakeholders in Australia, Europe, and United States, including world-leading universities and research institutes, industry partners, supercomputing centres, and government entities. In 2022, QB executed a world-first, deploying a quantum accelerator, operating in ambient conditions, at the Pawsey Supercomputing Centre in Australia. In 2023, QB launched Qristal, a software tool that uniquely enables developers to create applications for edge and massively parallelised quantum computers. Also in 2023, QB operated a quantum accelerator in the Australian bush, powered by as little energy as that emitted from a simple car battery, showcasing its huge potential for edge quantum computing and energy efficiency.

- **Quantum Diamonds**
  Founded in 2022 as a spin-off from the Technical University of Munich, QuantumDiamonds GmbH is led by CEO Kevin Berghoff and CTO Dr. Fleming Bruckmaier. The company specializes in commercializing advanced quantum-based wide-field imaging microscopes, primarily aimed at enhancing the failure analysis capabilities within the semiconductor industry. With a team of around 20 people, the company is providing testing services to customers already and is aiming to have commercial devices on the market in the near future.

- **Qzabre LLC**
  At QZabre, we offer high-performance, turnkey scanning Nitrogen Vacancy (NV) magnetometry microscopes, as well as scanning NV tips, pillar arrays, and customized diamond solutions. Scanning NV is revolutionizing the way magnetic and electric fields are measured at the nanometer scale. Our microscopes and scanning tips allow for the imaging of complex topological structures like skyrmions, traditionally inaccessible antiferromagnetic domains, ultrathin 2D magnets, and cycloids in multiferroic materials. Since spinning-off from ETH Zurich in 2018 we have made this technology accessible for academic as well as for industrial applications.

- **XeedQ**
  Since its founding in 2021, XeedQ GmbH has been working to enable early adopters with state-of-the art diamond spin based quantum computers. The company works closely with academia and research institutes enabling them to stay at the forefront of affordable quantum computers and solutions. The close collaboration with the academic and research is fostering technology development and USPs of diamond spins. XeedQ GmbH is one of the companies contracted by the German Aerospace agency to develop a scalable diamond based quantum computer. With the current scalability estimate of 64+ quits to 256+ qubits within 2030; XeedQ had already delivered five complete small scale diamond quantum computers to customers.